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SIMULATION OF INTEGRATED SURFACE WATER AND GROUND WATER SYSTEMS - MODEL FORMULATION[1]

Jiansheng Yan and Keith R. Smith[2]

ABSTRACT: The unique characteristics of the hydrogeologic system of south Florida (flat topography,sandy soils, high water table, and highly developed canal system) cause significant interactions between ground water and surface water systems. Interaction processes involve infiltration, evapotranspiration (ET), runoff, and exchange of flow (seepage) between streams and aquifers. These interaction processes cannot be accurately simulated by either a surface water model or a ground water model alone because surface water models generally oversimplify ground water movement and ground water models generally oversimplify surface water movement. Estimates of the many components of flow between surface water and ground water (such as recharge and ET) made by the two types of models are often inconsistent. The inconsistencies are the result of differences in the calibration components and the model structures, and can affect the confidence level of the model application. In order to improve model results, a framework for developing a model which integrates a surface water model and a ground water model is presented. Dade County, Florida, is used as an example in developing the concepts of the integrated model. The conceptual model is based on the need to evaluate water supply management options involving the conjunctive use of surface water and groundwater, as well as the evaluation of the impacts of proposed wellfields. The mathematical structure of the integrated model is based on the South Florida Water Management Model (SFWMM) (MacVicar *et al.*, 1984) and A Modular Three-Dimensional Finite-Difference Groundwater Flow Model (MODFLOW) (McDonald and Harbaugh, 1988).
(KEY TERMS: numerical model; ground water systems; surface water systems; resources planning; hydrogeology; water supply; water resources management.)

INTRODUCTION

In Dade County, Florida, most of the domestic, agricultural, and industrial water demands are supplied by ground water. Virtually all of the ground water withdrawals are from the unconfined to semi-unconfined Biscayne aquifer, which is the sole source of fresh ground water in the county. The Biscayne aquifer is recharged by rainfall and seepage from surface water bodies (water conservation areas and canals). Discharge from the Biscayne aquifer occurs through ground water withdrawals, evapotranspiration (ET), seepage to surface water bodies, and discharge to tidewaters (Figure 1). As a result of the extremely flat topography, highly permeable sandy soils, generally high water table elevation, and the extensive canal system, ground water levels are heavily influenced by rainfall, surface water stages, wellfield withdrawals, and ET. Losses from the aquifer through ET generally account for 60 percent to 80 percent of the annual total discharge. The canal system, originally designed for flood protection, now has a variety of functions including: 1) ground water recharge to the Biscayne aquifer during the dry season, 2) lowering ground water levels during the wet season to facilitate flood protection, 3) maintaining hydraulic barriers against saltwater intrusion and contaminant migration, and 4) importing water from Lake Okeechobee and the water conservation areas to meet urban and agricultural water demands.

When planning for water supply in Dade County, it is practical that proposed wellfields (such as the west wellfield in Dade County) be located near canals in order to take advantage of the potential recharge provided by the canal. This serves to reduce possible impacts to adjacent areas and prevent contaminant migration to the wellfield. Recharge from canals to the aquifer in and around wellfields is a significant part of the hydrologic regime. When evaluating water supply options that include new wellfields, a computer model can be used to simulate the hydrologic system of the area to predict possible impacts. Traditionally, the simulation is carried out following the procedure described below.

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[2]Respectively, Supervising Professional-Hydrogeologist and Director, Hydrogeology Division, South Florida Water Management District, 3301 Gun Club Road, P.O. Box 24680, West Palm Beach, Florida 33416-4680.

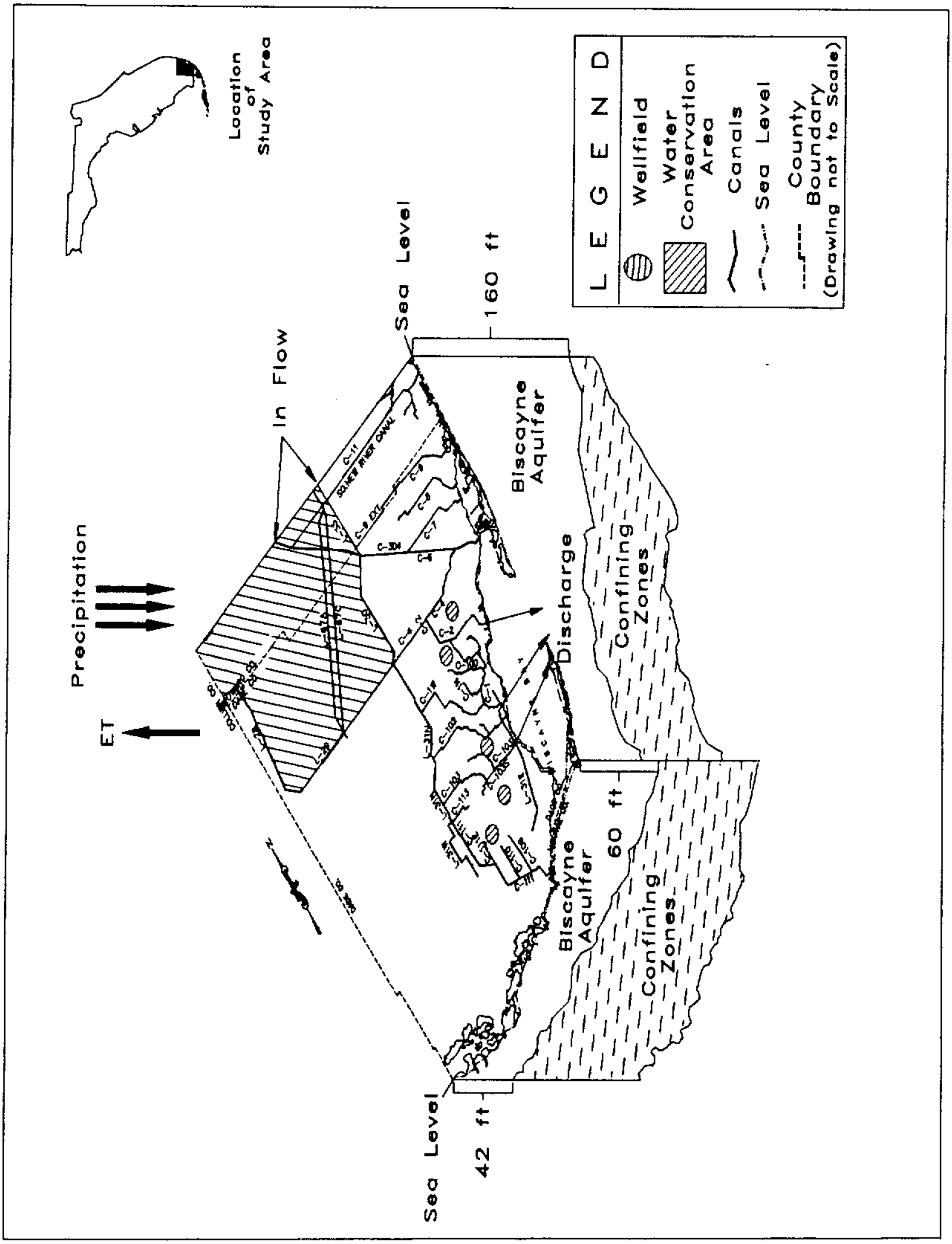

Figure 1. Dade County Hydrogeologic System.

Traditional Modeling Procedures

The traditional procedure begins with the development of a ground water model to simulate the ground water system. Surface water bodies are used as boundary conditions. Surface water stages are measured or estimated and used to set the head elevations in the boundaries. After the model is calibrated, the proposed wellfield is added to the model and the model is run again. Any changes in the results of the model runs are attributed to impacts caused by the proposed wellfield. Other modifications can be made to simulate future conditions, such as variations in recharge resulting from changes in land use, and altering consumptive uses of ground water to reflect increased demand. However, parameters such as rainfall and canal stages are usually either assumed to be the same during the predictive run as during the calibration period, or they are based on some other historical conditions.

A fundamental problem associated with this procedure when it is applied to south Florida conditions is that seepage from canals will increase significantly in response to pumping in an adjacent wellfield. This in turn causes a lowering of the canal stage, an increase in the flow delivered to the canal from outside the modeled area, or a combination of both. Most ground water models are not capable of simulating any of these situations. Consequently, simulations using a traditional ground water model may not be an accurate simulation of the entire hydrologic regime. These problems can be resolved by including simulation of surface water movement into the model.

Use of Two Models for Prediction

Since the effects of the surface water system need to be included to provide an accurate ground water model, it seems logical that the surface water movement and the canal stages can be predicted using a surface water model. Canal stages predicted by the surface water model can then be used as boundary conditions for the ground water model. Impacts from a proposed wellfield can be simulated by running the two models in this manner. However, when this approach is applied to south Florida conditions, several model components (recharge to ground water, ET, canal seepage) are often inconsistent between the two models, based on analysis of the water budgets of each model. With no direct and dynamic link between the two models, it is difficult to simulate the impact to the surface water system caused by a change in the ground water system (and vice versa). Results from each model must be incorporated into the other model through a manual interactive procedure that is cumbersome and may not produce reliable results.

The inconsistent results from surface water and ground water models are caused by the differences in both the model structures and the model calibration procedures. Surface water models are constructed and calibrated with emphasis on accurate estimation of stages and flows at specific locations. Emphasis is given to infiltration, ET, and surface water movement while oversimplifying ground water movement, interaction between surface water and ground water, and base flow generated by ground water. Ground water models are constructed and calibrated with emphasis on obtaining accurate ground water levels under the influence of stresses such as boundary conditions, wellfield pumpage, and recharge from surface water and rainfall while often ignoring or simplifying the infiltration and ET processes. Consequently, the accuracy of recharge and other model components is compromised, resulting in a less accurate model.

Additional inconsistencies between surface water and ground water models become apparent when comparing how time is simulated in each model. Surface water typically moves and reacts to stresses much faster than ground water. As a result, most surface water modelers will incorporate a relatively short time step or stress period (days or less) in which the ground water flow component can generally be overlooked. On the other hand, many ground water modelers will, depending on the situation, use a longer time step or stress period (months or years). In fact, it is not unusual to use a single, multi-year stress period to simulate long term impacts, although this practice now appears to be used less frequently than it once was. These factors, in addition to illustrating the different modeling approaches, must be addressed when using both a surface water and a ground water model to simulate a particular problem.

Both surface water and ground water models work well when used in areas where the interactions between the surface water and ground water are weak and ET from ground water is insignificant. However, in south Florida, particularly in Dade County, the magnitude of each of these two components is significant. Because the Biscayne aquifer is so close to land surface, it is in direct contact with the extensive canal system in most areas. Operation of the surface water system is the most important factor in the determination of ground water levels in the Biscayne aquifer. Because the canal system is so closely related to the ground water system, both surface water and ground water are of equal importance in model simulation and the development of water supply management options. The differing emphasis of the two types of models conflicts with the physical processes of the hydrologic system in the south Florida area.

Consequently, the inconsistencies generated by separately applying a surface water model and a ground water model make it difficult to produce accurate and reliable results for predictive purposes. These problems suggest that an integrated surface water/ground water model is needed for accurate simulation of the entire hydrologic system. This paper presents the methodology for resolving the problems and the mathematical formulation of the model implementing the methodology. Other components implementing the methodology will be described in a future paper.

THE INTEGRATED MODEL

The term "integrated model" is used to describe a model that is conceptualized and constructed with a reasonable level of detail regarding the simulation of surface water movement, ground water movement, and the interactions between the surface water and ground water systems. In addition, an integrated model is calibrated by using measurements of both surface water stages and flows and ground water levels. An integrated model can be constructed either by combining elements from surface water models and ground water models or by building a new model including simulation of the physical processes of both the surface water and ground water systems. Since numerous model codes have been developed to separately simulate surface water or ground water, the first alternative is preferred in most cases.

Most of the surface water models, such as Hydrological System Program-Fortran (HSPF) (Johanson *et al.*, 1984), Precipitation Runoff Modeling System (PRMS) (Leavesley, 1983), and Storm Water Management Model (SWMM) (Huber and Dickinson, 1988), are developed based on a basin and its subbasins (Figure 2) using the lumped parameter concept. These models describe every parameter with only one value for each subbasin. Most ground water models are developed based on the finite element or the finite difference schemes using the distributed parameter concept. The area to be simulated is discretized into cells (Figure 3). Each cell has a value for each parameter. The water movement is simulated as flow between cells.

A fully integrated surface and ground water model must be able to simulate the water movement both on the land surface and under the land surface, grid cell by grid cell. It must be able to simulate the water movement from the land surface to the aquifer (through the unsaturated zone) and between the aquifer and surface water bodies in both directions. In addition, ET from both the saturated and unsaturated zones must be simulated. To describe and track the movement of water accurately, the surface water movement must be simulated cell by cell corresponding to the cells of the ground water simulation. This requires modeling techniques different from those used in most surface water models.

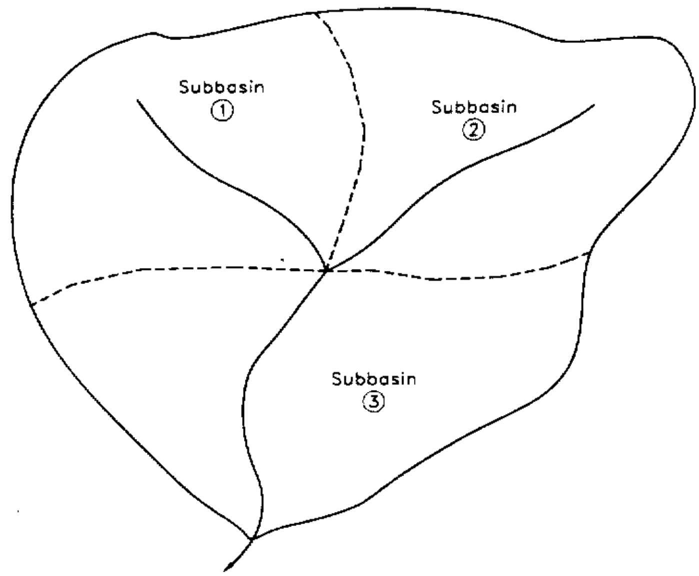

Figure 2. Model Building Scheme Used in Most of Surface Water Models.

Techniques simulating surface water movement cell by cell have been used in several models such as the ANSWERS (Areal, Non-point Source Watershed Environment Response Simulation) model (Beasley and Huggins, 1980) and the South Florida Water Management Model (SFWMM) (MacVicar *et al.*, 1984). These models use the distributed parameter concept that divides the watershed into square grid cells. Water from one cell can flow to adjacent cells with or without a channel. The SFWMM is actually an integrated model developed by the South Florida Water Management District. The model has been successfully used to simulate the water movement within the District on a regional scale. However, the model is developed using a relatively large grid (2 mile grid spacing) and a two-dimensional ground water simulation. It does not simulate cones of depression around wellfields, or flow in the unsaturated zone. The model code is "hard-wired" and difficult to change for scenario analysis or use in other areas. The concept presented in this paper is to modify SFWMM and integrate its surface water simulation with MODFLOW. The concepts and the equations used in the

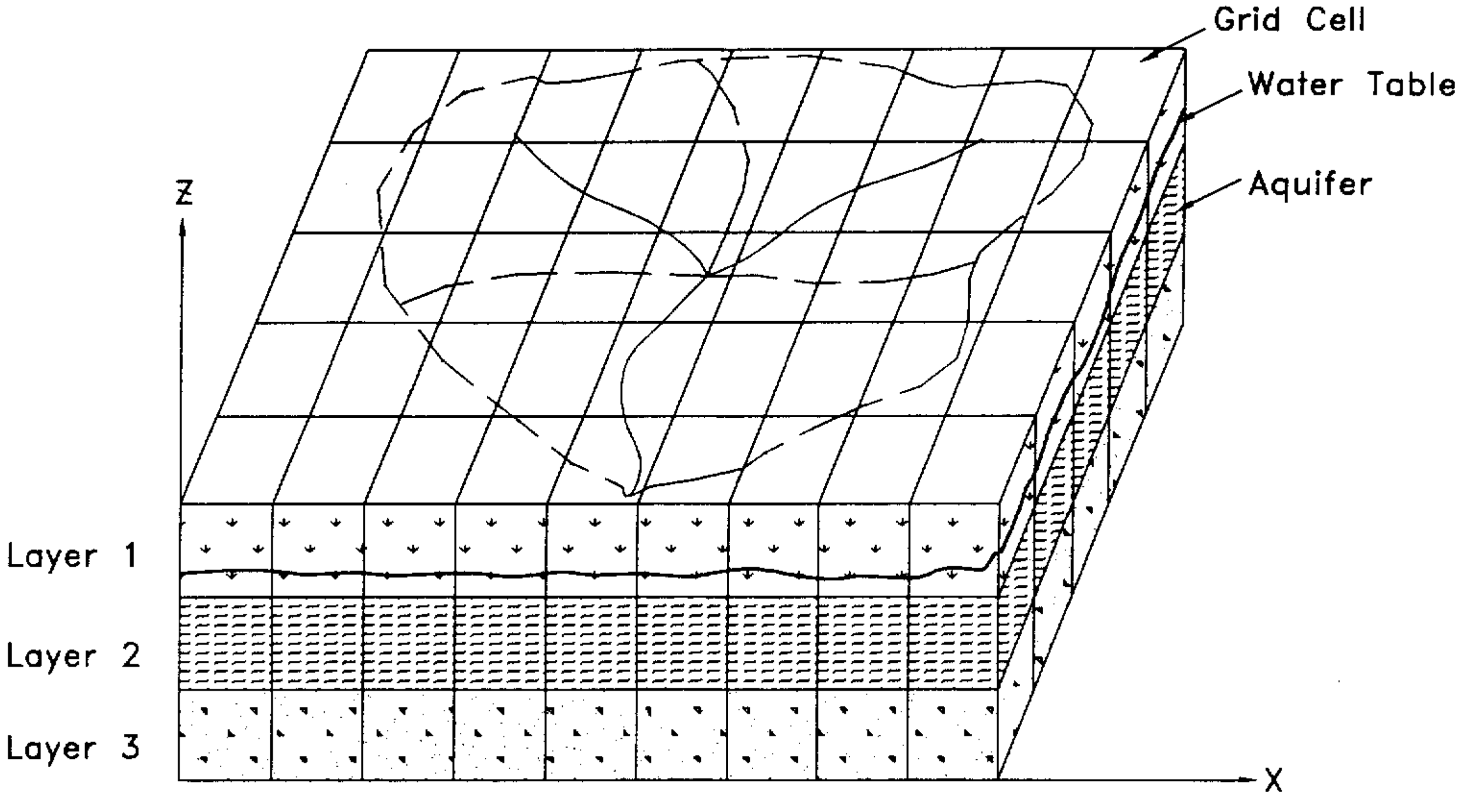

Figure 3. Model Building Scheme Used in Ground Water Models.

two models are applied, and the linkage and required modifications are discussed.

Approach

The movement of water outside of the aquifer is simulated using the SFWMM modeling schemes. The water movement within the aquifer system is simulated by MODFLOW. The two parts of the model are linked by the water movement between the surface water and ground water systems, which include recharge, infiltration, changes in soil moisture in the unsaturated zone, ET from the saturated and unsaturated zones, and flow between surface water bodies and the aquifer (both recharge and discharge).

Concepts

A schematic diagram of the conceptual integrated model is shown in Figure 4. For each of the uppermost cells in the model (Figure 3, Layer 1), the rainfall is first made available for interception by vegetation and depression storage on the land surface. For modeling purposes, interception and depression storage are lumped into one parameter called interception. Once the rainfall depth exceeds the available interception storage, water is then available for infiltration. When the rainfall intensity is greater than the infiltration rate and the interception storage is filled, the water starts to pond on the land surface and overland flow begins. Water which infiltrates moves into the unsaturated zone and increases the soil water content of the unsaturated zone. After the soil water content reaches the maximum soil water capacity, the water which infiltrates moves into the saturated zone as recharge. The overland flow moves from one cell to adjacent cells until it reaches a canal or a surface water body; water may also remain in a cell as ponded water depending on the hydraulic gradient between adjacent cells. The water in the canal flows from reach to reach; at the same time surface water may be recharged to ground water or ground water may be discharged into canals according to the hydraulic gradient and the operation of control structures. Water for ET is supplied by the three water components in the order of interception storage, soil water content in the unsaturated zone, and ground water in the saturated zone. Well pumpage and recharge are counted as direct stresses to the ground water system.

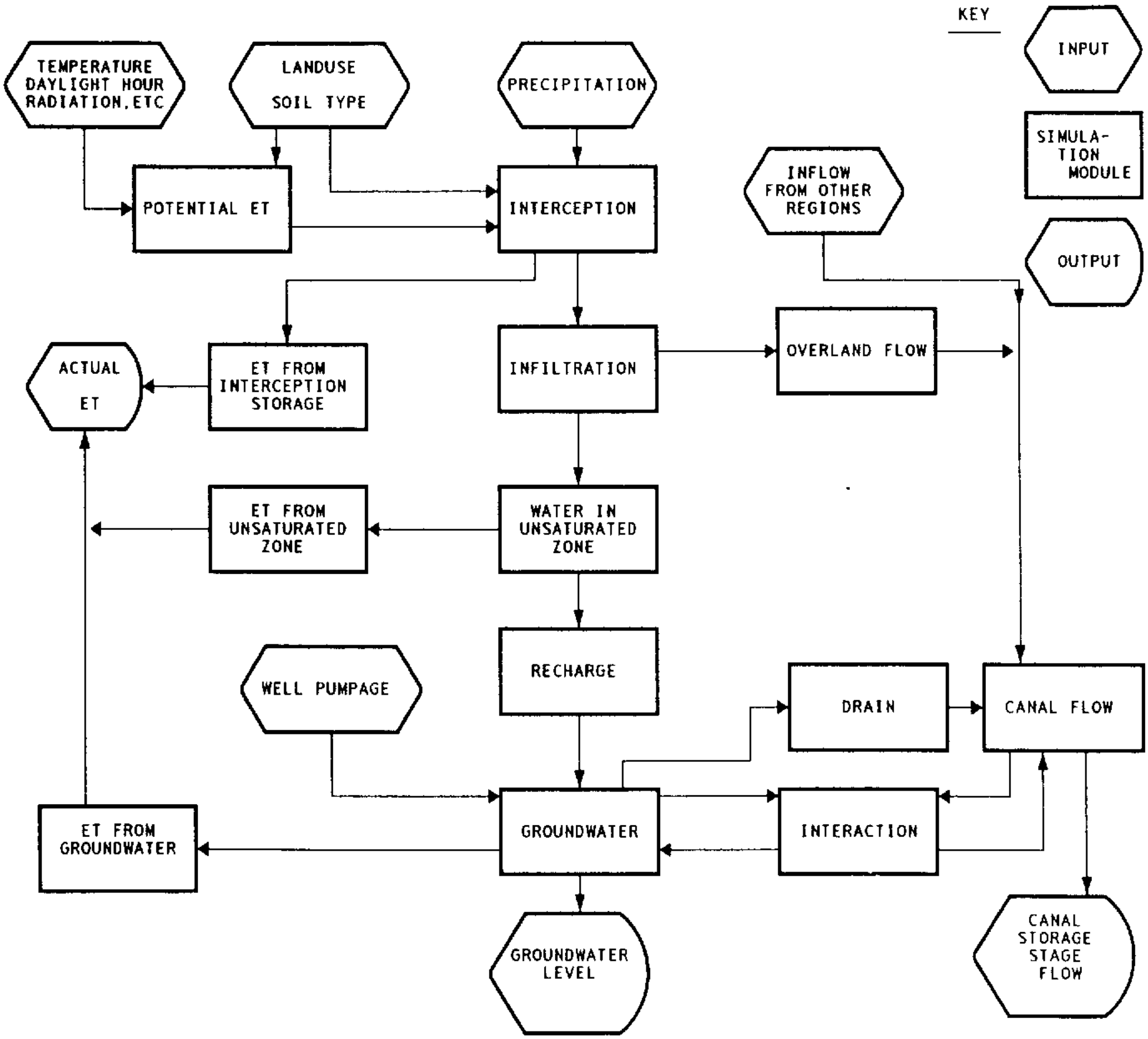

Figure 4. Schematic Diagram of the Conceptual Integrated Model.

In the model structure, each aspect of water movement is treated as a module. A main program is used to link the modules together and passes information among the modules. The mathematic equations for each module are presented in the following discussion.

Interception

Interception is considered as the sum of the precipitation intercepted by vegetation and the depression storage. A maximum interception storage volume in terms of "depth" over a grid cell, INT_m, is assigned to each grid cell according to the land use. For convenience, the volume will be expressed in terms of "depth" over a grid cell. The interception depth is filled by rainfall and depleted by evaporation.

Infiltration

At the beginning of each time step (daily), the rainfall depth for that time step is added to the surface ponding variable P_b after INT_m is filled, where P_b represents the surface ponding before infiltration is subtracted. A potential infiltration depth is calculated using a constant infiltration rate:

$$I_p = r(x,y)*DT \tag{1}$$

where I_p = the potential infiltration volume in terms of depth over a grid cell, r(x,y) = the constant infiltration rate, and DT = the time step in the calculation.

The infiltration volume is limited by the available soil storage volume (ASSV) in terms of depth over the grid cell:

$$ASSV = (S-\theta_0)*(E_l-h) \tag{2}$$

where S = soil storage coefficient on a volume basis (L^3/L^3), θ_0 = the average soil water content in the unsaturated zone at the beginning of the time step, E_l = the land surface elevation, and h = the ground water table elevation.

The actual infiltration (I_{act}) can be expressed as

$$I_{act} = Min\ \{P_b, I_p, ASSV\} \tag{3}$$

which is the minimum value of the three variables. Once the actual infiltration is determined, the ponding depth P is calculated as

$$P = P_b - I_{act} \tag{4}$$

Overland Flow

The overland flow movement is simulated by using Manning's equation. A roughness coefficient is assigned for each land use type. The overland flow between cells is defined as

$$Q_o = \frac{1.49W}{n\sqrt{L}} D^{\frac{5}{3}} \sqrt{H_u - H_d}\ \frac{DT}{2} \tag{5}$$

where Q_o = the volume of overland flow, W = the width of the grid cell or the length of the grid cell, n = the Manning's roughness coefficient, L = the length or the width of the grid cell, D = the average water depth between the two cells, and H_u, H_d = the upstream and the downstream stages of the overland flows, one is at the current cell, the other one is at the adjacent cell. DT is divided by two because Equation (5) is solved twice, once in the east-west direction, and once in the north-south direction.

The calculated flow volume is added to the ponding of the downstream cell and subtracted from the ponding of the upstream cell. The overland flow can only move to an adjacent cell within the same sub-basin as designated by a sub-basin indicator value. When a canal passes through a cell, the stage of the ponding in the cell is compared with the stage of the canal. If the stage in the cell is greater, the overland flow moves into the canal. If the overland flow volume is greater than the canal receiving capacity, the two stages will reach equilibrium; otherwise, the stage of the cell is reduced to the land surface and the volume removed is added to the canal storage. When the stage in the canal is greater, the water flows out of the canal until the two stages reach equilibrium.

Canal Flow

The term "canals" may be interpreted as including rivers, channels, ditches, or lakes, depending on the application. A mass balance procedure can be used to simulate the canal stage at the end of each time step. The canals can be defined as continuous channel reaches with flow control structures at the upstream and downstream ends. The canals may also be defined as lakes with a control structure or a definable relationship between the storage capacities and the stages at the downstream end.

A canal reach may receive inflow from upstream reaches, overland flow, and the discharge from the aquifer. Discharge from a canal reach can be outflow to downstream reaches and seepage to the underlying aquifer. The values of the inflows and outflows are calculated by referring to the stage values at the beginning of the time step. The differences of the inflows and the outflows are summed and added to the canal storage. The stage at the downstream end of the canal is obtained using the relationship between the canal storage and the stage. The canal stages at cell locations other than the downstream end are calculated as

$$STG = STGD + DIFFSTG * (L_c - L_d)/L_c \tag{6}$$

where STG = the stage at the center of the current cell, STGD = the stage at the downstream end, DIFFSTG = the stage difference of the upstream stage and the downstream stage, L_c = the total length of the canal, and L_d = the distance from the upstream end of the canal to the center of the current cell.

Water Exchange between Canals and Aquifers

The volume of the water exchange (V_{int}) between canals and aquifers is simulated using Darcy's law, which is based on the groundwater head (h) in the cell, the canal stage (STG), and the vertical hydraulic conductivity (K) of the canal bottom:

$$V_{int} = K*(STG-h)*L_{cc}*W_{cc}*DT/d \tag{7}$$

where L_{cc} = the length (reach) of canal in the grid cell, W_{cc} = the width of the canal, and d = the thickness of the canal bottom sedimentation.

When STG is greater than h, V_{int} is the recharge from the canal to the aquifer, and when STG is less than h, V_{int} is the discharge from the aquifer into the canal. Most ground water models use this equation to simulate the interaction between surface water and ground water. The equation describes an idealized situation (Figure 5) which may be quite different from the real situation as shown in Figure 6, which shows that the canal partially penetrates the aquifer and has low permeable sediments deposited on the canal bottom. The permeability of the sides of the canal may be much greater than that of the canal bottom due to the lack of low permeable sediments on the sides of the canal. Because of the resulting complex flow system around the canal, K and d values for an actual case are difficult to define. In a calibrated model, these parameters are usually determined as the result of the calibration process, and are not based on physical measurements. As a result, separate surface water and ground water models commonly generate different results because the K and d values for each model were generated by different calibration processes. However, if the integrated model is calibrated using measurements of both canal stages and adjacent ground water levels, K and d may be determined with a reasonable degree of confidence.

Evapotranspiration

The ET calculation is carried out in two steps: (1) calculate the potential evapotranspiration (ETp), and (2) calculate actual evapotranspiration (ETa). Since the potential evapotranspiration (ETp) can be calculated using any one of several available methods appropriate for the modeled area (Penman, Blaney-Criddle, pan, etc.), discussion will focus on the calculation of ETa. Actual ET depends on both the potential ET and the amount of water available to meet the potential ET. In the integrated model, water to meet ETp is supplied first from interception storage. If ETp exceeds INT_m, water available in the unsaturated zone will be supplied from the soil water content in the unsaturated zone. Finally, if ETp exceeds water available from interception storage and water in the unsaturated zone, water will be supplied from the saturated zone. Water available in the saturated zone for the rest of ETp depends on the depth of water table. ETa is the sum of water available to ET

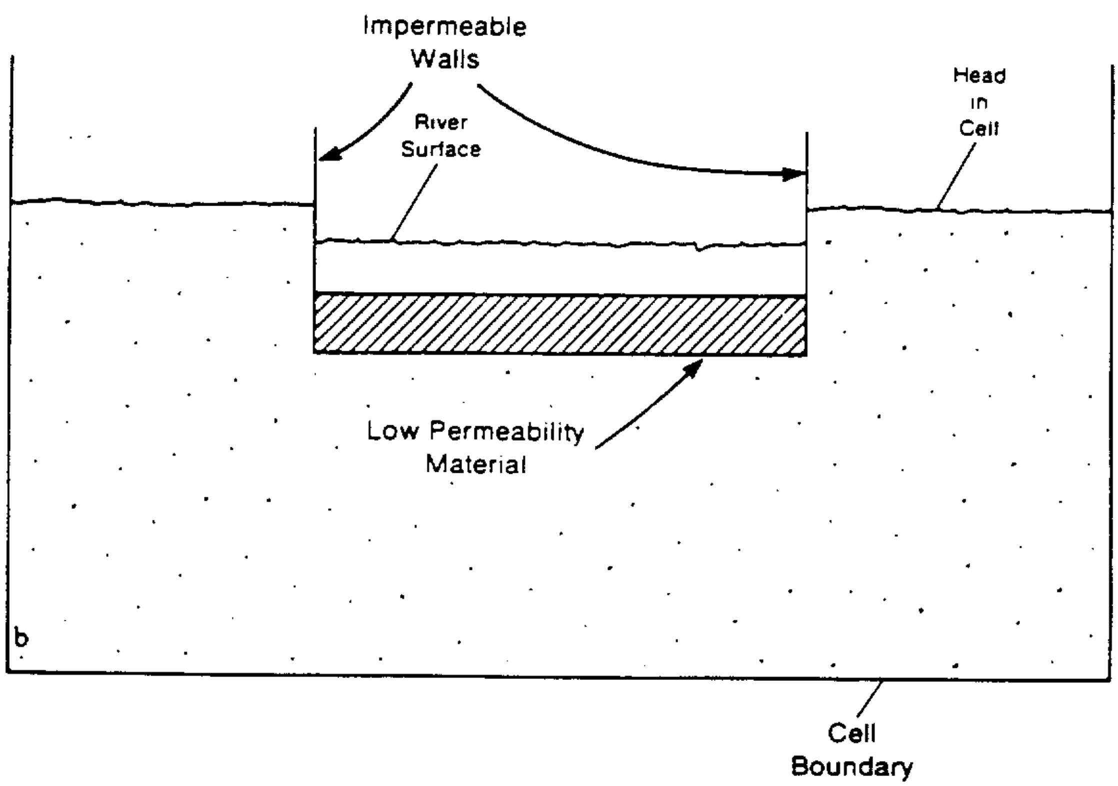

Figure 5. Conceptual Representation of the Stream-Aquifer Interaction Simulation (MODFLOW, Figure 33b)

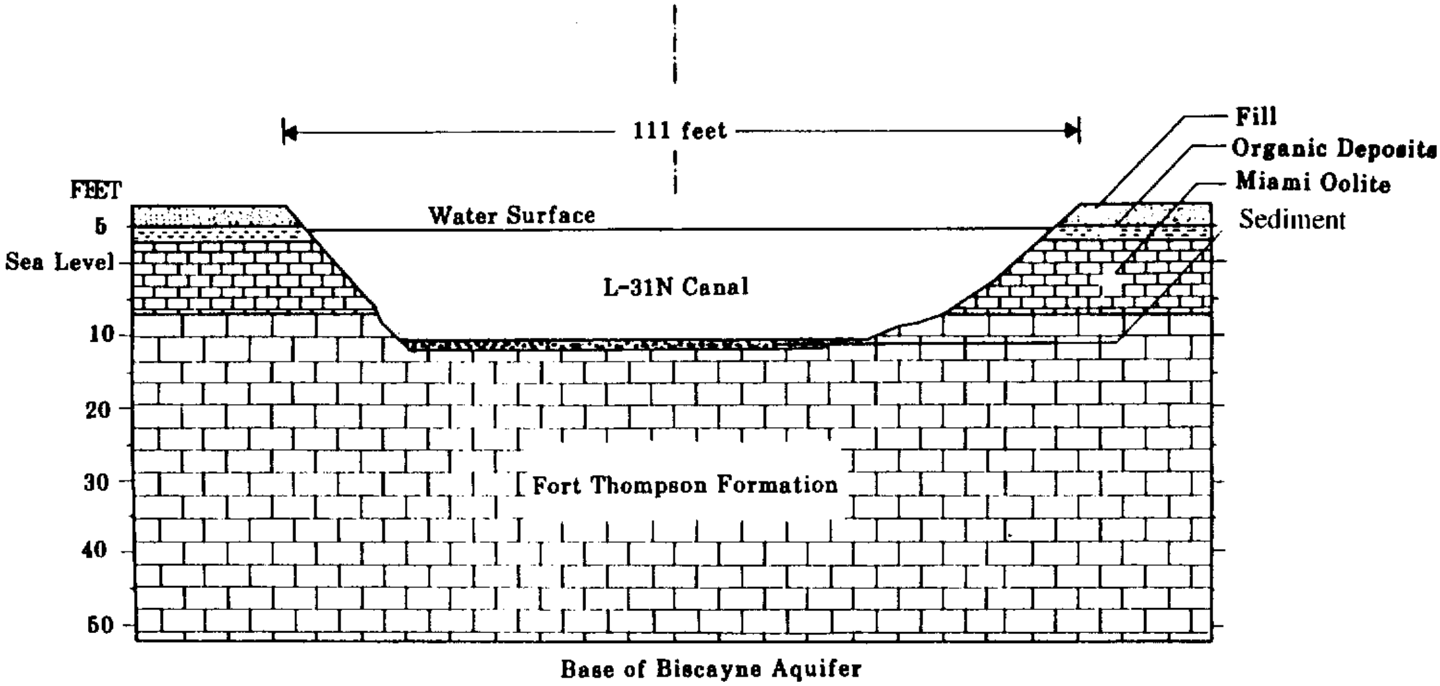

Figure 6. Cross-Section of the Aquifer Containing a Canal in Dade County (modified from USGS WRI Report 90-4135, Figure 6).

from all three sources. The simulation of ET from the unsaturated and saturated zones is described as follows.

The unsaturated zone is defined as the zone above the water table and below land surface. The thickness of the unsaturated zone varies as the water table fluctuates. The soil water content in the unsaturated zone is assumed to vary from a maximum soil water capacity $\theta_{max}(Z_d)$ to a minimum soil moisture amount $\theta_{min}(Z_d)$. Z_d is the water table depth below the land surface.

$\theta_{max}(Z_d)$ represents the average maximum water capacity over a moisture profile, which corresponds to an equilibrium stage of the recharge process with respect to the water table depth. The equilibrium stage can be reached in two ways:

1. The average soil water content increases to $\theta_{max}(Z_d)$ through infiltration from rainfall without significantly altering the water table depth. However, if rainfall continues after $\theta_{max}(Z_d)$ has been reached, the additional infiltration recharges directly to the water table causing it to rise, or

2. The average soil water content is greater than the $\theta_{max}(Z_d)$ and infiltration from rainfall reaches the water table. After rainfall stops, the soil water content starts to decrease (drain) until the soil water content reaches $\theta_{max}(Z_d)$ and the water table stops rising.

Three typical soil water content distribution profiles with respect to three water table depths at the equilibrium stage are shown in Figure 7. $\theta_{max}(Z_d)$ can be expressed as an average soil water content over the unsaturated zone as follows:

$$\theta_{\max}(Z_d) = \frac{1}{Z_d} \int_{z=0}^{z=Z_d} \theta(z)dz \tag{8}$$

where $\theta(z)$ is the soil water content at depth z, which varies from θ_{fc} at z=0 and θ_{sat} at $z=Z_d$. θ_{fc} and θ_{sat} are field capacity and saturated soil water content, respectively. Since the soil moisture profiles at their equilibrium stages vary with respect to the water table depths, the average $\theta_{max}(Z_d)$ varies with respect to water table depth (Z_d). The average soil water contents θ_{max1}, θ_{max2}, and θ_{max3}, are correspondent at the depths $z=Z_{d1}$, $z=Z_{d2}$, and $z=Z_{d3}$. For a shallow water table, the moisture profile is shown by the upper right solid curve in Figure 7. The exact shape of the curve is determined through experiment. As the water table depth increases, the average soil water content decreases and approaches θ_{fc} at a large water table depth (Z_{ext}), which is the extinction depth defined in MODFLOW. Since the dynamic change of soil water content is quite complicated, it is not practical to integrate over the soil moisture distribution curve for each water table depth. $\theta_{max}(Z_d)$ can be assumed to be a linear function of water table depth as shown in Figure 8 by the solid line.

may vary from 0.03 to 0.20 for $\theta_{min}(Z_d)$, and from 0.11 to 0.37 for $\theta_{max}(Z_d)$.

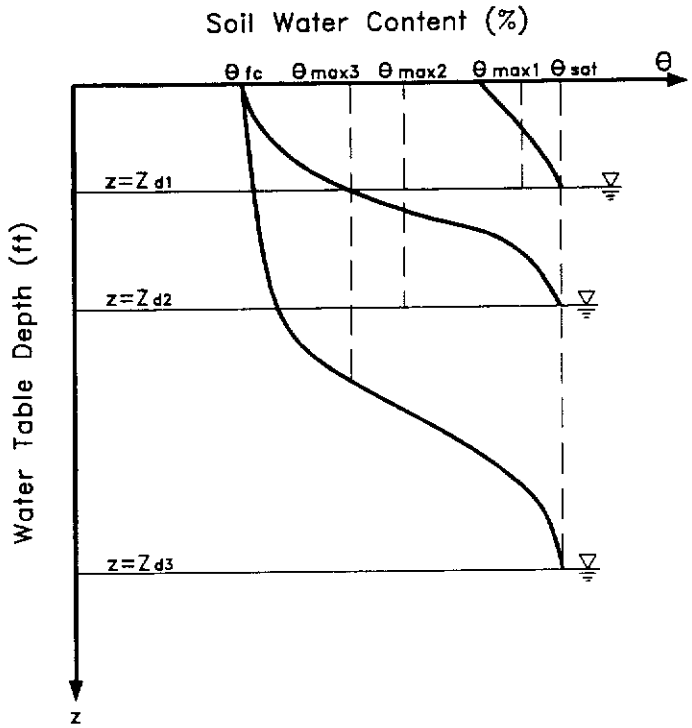

Figure 7. Schematic Equilibrium Water Content Distribution.

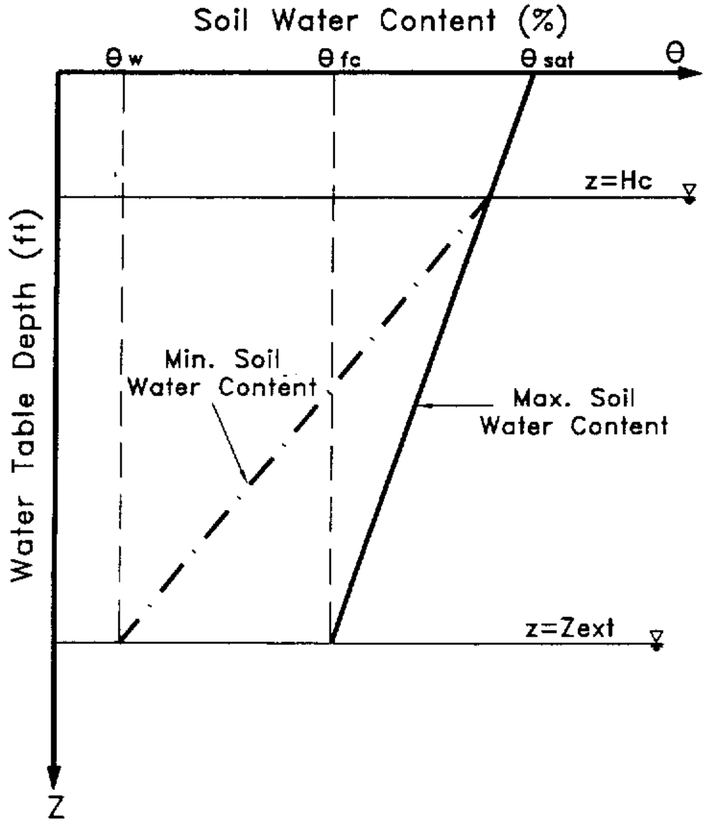

Figure 8. The Averaged Maximum and Minimum Soil Water Content Corresponding to Water Table Depth.

The minimum soil moisture content ($\theta_{min}(Z_d)$) is defined as the average minimum water capacity over a soil moisture profile

$$\theta_{\min}(Z_d) = \frac{1}{Z_d} \int_{z=0}^{z=Z_d} \theta(z)dz \tag{9}$$

where $\theta(z)$ varies from θ_w at $z = 0$ to θ_{sat} at $z = Z_d$. $\theta_{min}(Z_d)$ corresponds to an equilibrium stage of the ET process with respect to the water table depth. Once the soil moisture profile reaches the equilibrium stage, additional water needed by crops is taken from the saturated zone by upward flux. The relationship between $\theta_{min}(Z_d)$ and ground water table is shown in Figure 8. In Figure 8, Hc is the capillary fringe related to soil type, θ_w is the soil water content at the wilting point. When $z \le Hc$, $\theta_{max}(Z_d)$ and $\theta_{min}(Z_d)$ are equal. When $Hc < z \le Z_{ext}$, $\theta_{max}(Z_d) > \theta_{min}(Z_d)$. When $z > Z_{ext}$, $\theta_{max}(Z_d) = \theta_{fc}$ and $\theta_{min}(Z_d) = \theta_w$. $\theta_{max}(Z_d)$ and $\theta_{min}(Z_d)$ can be estimated based on the soil studies and adjusted in a calibration process. Typical values

In brief, based on the definitions and assumptions discussed, the ET process takes place in three ways:

1. If the soil moisture is greater than $\theta_{min}(Z_d)$, water in the unsaturated zone will supply the water lost to ET until the soil moisture drops to $\theta_{min}(Z_d)$. Then, the ET may be supplied by upward transport of the water from the saturated zone, and the amount of water which can be transported upward from the saturated zone depends on the depth of the water table,

2. If the soil water content in the unsaturated zone is sufficient to meet the potential ET, no ET will be taken from the saturated zone.

3. If the amount of water available from the unsaturated zone is equal to $\theta_{min}(Z_d)$, ET is taken only from the saturated zone and can be estimated using a linear ET function that is similar to the ET package in MODFLOW.

Recharge by Rainfall

As previously discussed, water supplied by precipitation fills the interception storage first. Once the available interception storage is filled, infiltration begins. Water which infiltrates moves into the unsaturated zone and increases the soil water content within the unsaturated zone. It is assumed that after the soil water content reaches the maximum soil water capacity, water which continues to infiltrate moves into the saturated zone as recharge. The volume of recharge is calculated as

$$Q_r = I_{act} - (\theta_{max} - \theta_o)(E_l - h) \tag{10}$$

where Q_r = the volume of recharge to groundwater from rainfall, θ_o = the soil water content in the unsaturated zone at the beginning of the time step, I_{act} = the actual infiltration, and E_l = the land surface elevation;

and

$$Q_r = 0.0 \qquad \text{for } I_{act} <= (\theta_{max} - \theta_o)(E_l - h). \tag{11}$$

Groundwater Module

The ground water model (MODFLOW) is a module within the integrated model. The ground water module takes the recharge, ET deficit, and canal stages calculated by other modules as input. The ground water module then simulates the water movement in the aquifer under all the applied stresses. The output, such as the ground water levels of the uppermost layer, are sent back to other modules at the end of the time step. The governing equation of the ground water flow is

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)$$

$$= S_s\frac{\partial h}{\partial t} \pm \sum Q_w \tag{12}$$

where K_{xx} = the components of the hydraulic conductivity in the x direction, K_{yy} = the components of the hydraulic conductivity in the y direction, K_{zz} = the components of the hydraulic conductivity in the z direction, S_s = the specific storage per unit change in the hydraulic head, and Q_w = the recharge or discharge from the aquifer (i.e. recharge, ET, etc.).

DISCUSSION

The previous discussion provides a conceptual framework for an integrated ground water and surface water model. The integrated model employs procedures used in traditional surface water models to estimate the infiltration component of recharge. Other components of recharge (canal seepage, recharge wells) are simulated through other modules. The model uses an estimation approach for simulating ET from the unsaturated and saturated zones. The model simulates all water movements cell by cell, and provides a dynamic linkage between surface water and ground water. Compared to the traditional procedure and the use of separate surface water models and ground water models for simulation, the integrated model has both advantages and disadvantages.

Advantages

The integrated model simulates the entire hydrologic system in an area. Any change in the ground water system will be reflected in the surface water system (if appropriate), and vice versa. This dynamic linkage between the two systems makes the model more suitable for use in simulating the hydrologic system in south Florida, where surface water and ground water systems are closely related.

Since the integrated model must be calibrated using surface water stages and flows as well as ground water levels, the model parameters and components which are not measurable will more accurately represent their actual values than if separate models were used. For example, if the measured canal stages and the ground water levels near the canal are matched with model outputs, the estimate of the canal bottom conductance should more closely represent the true value. Generally, as more measurements are used for model calibration, a more reliable and accurate model will result. The inconsistency between model results from using two separate models is eliminated. Finally, the model is easier to use for generating an optimum water management strategy for the conjunctive use of surface water and ground water.

Disadvantages

The model is more complex and more computing time is needed. Two kinds of measurements (surface water stages/flows and ground water levels) need to be matched with the model outputs. This results in a multi-objective problem for model calibration from the point of view of parameter optimization. The model calibration is more difficult than the calibration of the two separate models.

SUMMARY

A conceptual integrated surface water and ground water model is presented. The model is based on the need to evaluate water supply plans involving the conjunctive use of surface water and ground water, as well as the evaluation of the impacts of proposed wellfields. Inconsistent results are likely to be generated when two separate models are used to simulate the highly interactive surface water and ground water systems. When model results are inconsistent or the pre-defined boundary conditions in the ground water model cannot reflect the corresponding changes to canal stages or flows that may be caused by stresses to the ground water system (i.e., new or proposed wellfield pumpage), the model results may not meet the level of accuracy necessary for the model to be used with confidence as a planning tool. The integrated model simulates the entire hydrologic system by following the physical processes of the south Florida hydrologic system with a cell by cell surface water simulation, unsaturated soil water simulation, and a three-dimensional ground water simulation. New approaches to simulate the ET and recharge processes are also included in the integrated model. A dynamic link between the surface water system and ground water system is provided. The model will be calibrated using the measured stages and flows in canals, as well as ground water levels. It is expected that the integrated model will improve the results generated by using a surface water model and a ground water model separately.

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